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Connective Heating Improvement for Emergency Fire Shelters

Composition and Performance of Fire Shelter Concepts at Close-Out

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Contents

Introduction	1
CHIEFS Initial Small Scale Sample Development	2
First Generation (Gen 1) Full Scale Shelter Development	3
Second Generation (Gen 2) Full Scale Shelter Development	4
PTFE Gas Barrier Replacement and Close-Out Full Scale Shelter Development	6
Small-Scale Convective Test Setup.....	7
Full Scale Shelter Test Setup.....	8
Close-out Shelter Layups.....	11
Full Scale Close-Out Shelters.....	16
Full Scale Shelter Test Criterion.....	17
Full Scale Shelter Test Results	18
Small-Scale Convective Test Results	28
Concluding Remarks.....	29
References.....	31

Table of Figures

Figure 1: CHIEFS generation 1 geometry "Thermal Pod"	4
Figure 2: CHIEFS MW shelter geometry.....	5
Figure 3: CHIEFS small scale convective test setup.	7
Figure 4: small scale convective test setup schematic.	8
Figure 5: Full scale shelter test apparatus without enclosure. Instrumentation (top), and deployed test article (bottom).	8
Figure 6: Full scale shelter test apparatus at the university of Alberta with flames on during tests.	10
Figure 7: Layup of current M2002 shelter.....	11
Figure 8: Existing fire shelter (M2002) [12].....	12
Figure 9: UAI fiberglass insulation batting.....	14

Figure 10: UAI fiberglass insulation with embedded intumescent graphite flakes and scrim.....	15
Figure 11: Graphical depiction of CHIEFS close-out shelter layups.	15
Figure 12: Average total heat flux outside of shelters recorded by Medtherm sensors for all tests.	19
Figure 13: Averaged 2-inch "breathing zone" thermocouple data summary.....	20
Figure 14: Averaged 10-inch thermocouple data summary.....	21
Figure 15: Averaged internal radiant heat flux data summary.....	22
Figure 16: Averaged internal carbon monoxide concentration data summary.	23
Figure 17: Averaged internal oxygen concentration data summary.....	24
Figure 18: White powder covering shelter interior instrumentation after the conclusion of a Single Silicone shelter test.	25
Figure 19: Typical M2002 interior post-test condition.	25
Figure 20: Interior video data showing subjective smoke concentration inside a Single Silicone shelter at three times: test criterion failure (87 seconds, TOP), test conclusion (119 seconds, MIDDLE), and conclusion of video data (152 seconds, BOTTOM).	26
Figure 21: Typical Single interior post-test condition.	27
Figure 22: Close up of UAI post-test condition in Single shelter.	27
Figure 23: Typical Double shelter interior post-test condition.	27
Figure 24: Small scale convective test rig results of layups used on full scale close-out shelters tested. ...	29

Introduction

On June 30th 2013, 19 members of the Granite Mountain Interagency Hotshot Crew lost their lives in a wild fire outside of the town of Yarnell Hill, Arizona. The fire fighters were entrapped after weather conditions rapidly changed fire behavior, and were forced to begin clearing dense brush and other fuels in order to make a deployment site for their emergency fire shelters. The emergency fire shelter currently issued to wild land fire fighters, known as the M2002, is an excellent design to efficiently reflect radiant energy; however, the shelter is not able to withstand prolonged exposure to direct flame contact. As a result, firefighters are trained to clear fuels away from the vicinity of their deployed shelter before flames encroach. According to the official investigation report, the crew members had less than two minutes to use chainsaws, shovels, and other tools to remove fuels from the Yarnell Hill deployment site [1]. It is apparent that this was not enough time to complete the task; the hotshots had not yet finished clearing the site when the flame front overtook them and only some of the crew were found inside of a fully deployed fire shelter. Temperatures of over 1100°C (2000°F) were evident at the site; there were no survivors. News of this tragedy spread around the country, and researchers at NASA Langley Research Center saw an opportunity to help prevent future tragedies like Yarnell Hill by utilizing their experience developing Flexible Thermal Protection Systems (FTPS) for inflatable decelerators to improve the shelter's ability to withstand exposure to flames.

For approximately the past 10 years, NASA Langley Research Center has been engaged in the development of FTPS for use on Hypersonic Inflatable Aerodynamic Decelerators (HIAD) for atmospheric entry [2, 3]. These inflatable decelerators could be exposed to peak, cold wall heat flux values up to 100 W/cm². The decelerator is constructed of an inflatable structure which is protected from heating by an outer FTPS covering. The inflatable structure is composed of high strength polymer membranes, bands, and straps; therefore, this structure needs to be kept at a relatively low temperature in order to maintain its required mechanical strength. Maintaining a temperature below material limits on the inflatable structure throughout the duration of entry is the purpose of the FTPS.

As the name suggests, FTPS differs from traditional rigid heat shield thermal materials in that it must be flexible. Inflatable decelerators are designed to be packaged and stowed into launch vehicles whose diameters are more than 5 times smaller than the diameter of the fully inflated structure. As a result, FTPS materials must be able to be folded and compressed when packed without serious deleterious effect to thermal protection when deployed. As with any flight article, packed mass and volume are primary constraints in the development of FTPS; to date, a typical inflatable heat shield FTPS concept is less than 25.4 mm (1 inch) thick with an areal mass of 3.1 kg/m² (0.6 lb/ft²) to withstand a 10 kJ/cm² integrated heat load Earth entry trajectory. As a result, research into FTPS materials focuses on identifying candidates with high thermal efficiency, or, high thermal resistance with minimal mass and thickness. Thermally efficient designs are realized both by utilizing high performance materials and also by applying these materials to specific heating regions within the internal FTPS layup where they are optimally suited to inhibit heat transfer.

FTPS is composed of a stack of different thermal materials known as a "layup". The outer regions of the layup are exposed to higher temperatures than the inner regions of the FTPS which lie closer to the underlying inflatable support structure. For this reason, materials in the outer region should inhibit heat transfer best at relatively higher temperatures compared with

the inner region. The outer most layer in the FTPS layup is a refractory structural fabric intended to protect underlying insulations from shear flow forces and possesses optical properties favorable for rejecting radiant energy from the surface. Heat transfer in high temperatures is dominated by radiant transmission; therefore, a preferred configuration is materials in the higher temperature region of the layup that are internally composed of radiant reflectors or opacifiers to reduce heat transmission toward the underlying structure. Inner, cooler regions predominantly focus on the inhibition of gas conduction, which is the dominant heat transfer mode in this region. The inner-most layer in the FTPS layup is the gas barrier. The gas barrier is designed to dead-head high temperature gas advection through the permeable insulation layers and protect the underlying structure from hot gas impingement. Traditionally, projects involved in research and development of FTPS for inflatable structures test material samples in an arc-jet tunnel and iteratively evaluate various candidate materials in order to converge on optimum material configurations that provide maximum thermal efficiency for a target trajectory.

CHIEFS Initial Small Scale Sample Development

In the fall of 2013, NASA Langley Research Center began an effort called Convective Heating Improvement for Emergency Fire Shelters (CHIEFS). CHIEFS operated on the premise that lessons learned, test methodology, and technological advances realized over the past decade of NASA FTPS development could be applied directly to the fire shelter application due to several key similarities between atmospheric decelerators and fire shelters. Both applications require durable flexible materials which can be packed to a minimal stowed volume, but be rapidly deployed for a single use to deliver predictable protection when exposed to a short duration and high intensity heat pulse.

Despite the many similarities between FTPS technology for inflatable decelerators and fire shelter layups, several key differences were identified which made it necessary to focus the CHIEFS effort on developing a dedicated layup for the fire shelter application. The forest fire environment is different from that of atmospheric re-entry partly due to the presence of oxygen at the Earth's surface; several materials primarily composed of carbon – which exhibit desirable characteristics on decelerators where reduced oxygen levels are present – decompose exothermally upon heating in a fire shelter layup test. Also, peak re-entry heating occurs at high altitudes with corresponding low static pressures; so, radiation is a more dominant mode of heat transfer in FTPS for decelerators. Fire shelters would benefit from layups with more emphasis on addressing gas conduction. Cost is an additional consideration for the fire shelter. Currently, the M2002 costs less than \$400 per unit, and keeping the shelter within range of this price eliminates the use of many exotic materials which have been investigated for FTPS. There are additional considerations for the fire shelter due to the fact that it is occupied by a human being during use. For example, it is not desirable to use materials with overly toxic or harmful decomposition byproducts, and such compounds should not be allowed to accumulate to considerable concentrations inside the shelter. Finally, mass and volume constraints on the fire shelter are significantly different than on the inflatable decelerator. The heating environment expected for the fire shelter is far lower. Current FTPS candidates are tested to peak heating rates between about 5 and 10 times higher than average values reported in forest fire research; therefore, the M2002 wall thickness of less than 1 mm makes direct application of a nearly 25.4 mm-thick FTPS layup inappropriate. Additionally, crew in the field are required to carry up to 18.1 kg (40 lb) of gear; and, according to a 2014 survey many firefighters already consider the 1.95 kg (4.3 lb) M2002 too heavy [4]. Significantly increasing convective protection without noticeably increasing shelter mass or packed volume has proven a challenging proposition.

CHIEFS began in 2014 by conducting a series of small-scale laboratory convective tests at NASA Langley Research Center. The small scale test setup, initially a duplicate of test equipment used by the USFS to conduct similar testing, will be discussed in subsequent sections, as well as in previously published reports [5, 6]. The primary focus of this initial testing was to rapidly screen various material options to assess the likelihood of developing a future layup with sufficient thermal efficiency to make a significant convective improvement to the M2002 layup without incurring significant increases in mass, volume, or cost. By October 2014 CHIEFS had screened over 100 unique material layups and demonstrated significant improvement to the convective performance of the M2002 layup. At that time, the CHIEFS team met with USFS Missoula Technology and Development Center (MTDC) personnel and presented current research results at a Technical Interchange Meeting (TIM).

MTDC had already been directed by the Washington Office Fire and Aviation Management (WO-FAM) to accelerate the lifecycle product review for the fire shelter and supporting components (a planned effort to assess materials available for a possible fire shelter revision). This action was taken largely in response to the Yarnell Hill tragedy, and MTDC responded favorably to the exploratory results presented by CHIEFS. In early 2015, NASA and the U.S. Forest Service entered into an Interagency Agreement and an open exchange of research findings and test collaboration ensued.

First Generation (Gen 1) Full Scale Shelter Development

After the TIM, CHIEFS resumed small-scale testing. With the intention of future full-scale shelter fabrication in mind, further improvements to the thermal efficiency of material layup candidates were investigated. Additionally, considerations required to enable the practical construction of a full-scale shelter were investigated. For example, materials not durable enough to be folded or sewn were discarded from the test matrix. An approach was developed to provide options with a range of protection and document their associated mass and volume costs.

With guidance from MTDC, the effort focused on the development of optimized light, medium, and heavy-weight layups. The goal was to provide a shelter option that offered similar thermal protection to the M2002 but weighed less (light-weight), a shelter that weighed about the same as the M2002 but offered better protection (medium-weight), and an option that provided significantly better protection but was heavier (heavy-weight). The heavy-weight option was likely to be too heavy to be carried by individual firefighters on foot, but may be considered as an option for equipment operators who are never far from vehicles where a shelter with significant protection could be stowed.

In an effort to offset mass and packed volume, alternate shelter geometries were investigated. By finding a design which provided acceptable occupancy and breathing air volume but reduced wall surface area, heavier layups could be used without incurring as much additional mass as would be evident if these layups were installed on the full scale M2002 geometry. Multiple options were investigated, and an initial design known as the “Thermal Pod” was decided upon as shown in Figure 1.



**FIGURE 1: CHIEFS GENERATION 1 GEOMETRY
"THERMAL POD".**

The Thermal Pod targeted the geometric efficiency of a sphere to achieve a design that uses about 20% less surface area than the M2002, and also decreased the surface area to volume ratio of the shelter, a configuration favorable to slower heating of the interior environment. Shelters were also manufactured with the standard M2002 geometry and NASA-selected materials. A total of 12 shelters were manufactured: three light-weight using the M2002 geometry, three medium-weight using the Thermal Pod geometry, and six heavy-weight shelters (three of the M2002 geometry and three of the thermal pod geometry). These were

CHIEFS' first generation shelters. One of each of these shelters was exposed to controlled wild fire burns in Northwest Territories of Canada in June 2015, and the remaining shelters were subjected to full-scale laboratory tests at the University of Alberta in September of 2015. The opportunity to participate in the Northwest Territories burns accelerated research efforts from small-scale laboratory tests to full scale shelter fabrication and testing in a period of about five months. Full scale first generation shelter testing demonstrated encouraging thermal performance within the overall weight and volume regime; however, testing also revealed that future work was required to identify shelter seam designs that better prevent smoke and gasses from entering the shelter as well as to take into consideration the decomposition byproducts of shelter materials when heated and their associated toxicity and flammability levels.

Second Generation (Gen 2) Full Scale Shelter Development

Based on discussions with USFS in October 2015 it was decided to begin work on a second generation of NASA fire shelters, known as "Gen 2". The emphasis of the Gen 2 effort was on using materials with less volatile and toxic decomposition byproducts, seams with better sealing capability, as well as a continuation of the push toward higher technology readiness level, durable, and affordable materials.

At present, a fire fighter can purchase an M2002 fire shelter ready for use for under \$400; the CHIEFS team needed to keep this price point in mind when selecting materials in order to provide a practical shelter option. An informal survey, administered by the USFS to fire fighters, indicated a preliminary reluctance to the design of the Thermal Pod concept. Although this survey was not conducted across a wide group of firefighters, and responses seemed to indicate common misunderstandings in the questions asked, it was decided that emphasis would be placed on using the existing M2002 regular-length geometry with a potential for future investigations of slimmer-width or lower-height M2002 designs to reduce overall weight and packed volume if necessary.

Some of the Gen 2 shelter development and testing is covered in previous writing by Fody, et. al. [5]. This reference includes descriptions of shelter layups, small-scale laboratory tests, and full scale tests conducted on ten shelters at North Carolina State University (NCSU) in early March 2016. Test results from NCSU, including video taken inside the shelters during heating, indicated that significant heat and combustible gasses were entering the shelter through the wall seams prior to any significant degradation in the surrounding wall material. On occasions internal flaming and/or combustion was observed after these gasses had

accumulated for some time. Consequently, much of the testing conducted at NCSU focused on screening various shelter wall seam construction concepts in search of a design that was both relatively impermeable as well as practical to manufacture in full scale production. Additional testing was conducted at NCSU during the summer of 2016, with top performing shelter candidates carried forward to testing at the University of Alberta with the USFS in September of that year.

Nine unique full scale shelter candidates were tested at the University of Alberta in September 2016, also covered in previous writing by Fody, et. al. [6]. These shelters were variations of five unique wall material layups, four seam construction concepts, and two shelter geometries. The shelter geometries tested were mostly the standard M2002 shape; however, a modified concept developed by NASA known as the “MW” shelter was also tested. The MW design was approximately the same size and shape as the M2002; however, rather than the spherical end caps used by the M2002 (created by the use of three darts) a continuous seam ran down the length of the shelter at the centerline. By producing this shelter with only one seam, using only two panels, the manufacturing was simplified and there was some reduction in shelter weight as well. Another advantage of the MW concept was that the running seam length was reduced; seams were suspected to be a source of hot and combustible gasses entering the shelter. The MW shelter concept can be seen in Figure 2.



FIGURE 2: CHIEFS MW SHELTER GEOMETRY.

Shelter performance during the September 2016 tests were generally good, exhibiting an average increase in shelter habitability of about 60% compared to the M2002, and were used to drive key design decisions moving forward. At this point, shelter habitability began to be defined by finding the earliest failure of several variables including but not limited to exceeding a maximum shelter interior carbon monoxide limit, minimum oxygen limit, and maximum breathing zone temperature. The layup known as “PDS3” exhibited the best performance (average habitability time of 104 seconds compared with the M2002 at 56 seconds); this layup was consequently carried forward as the baseline for the close-out shelter concepts described in greater detail in the “Close-Out Shelter Layups” section of this paper. The MW geometry showed a slight improvement in thermal performance when compared to an equivalent M2002 geometry shelter (about a 9% improvement in habitability time). Contrary to test results at NCSU, the tests at the University of Alberta showed only minimal advantage of any of the more complicated seam construction designs tested compared with the standard M2002 wall seam. The M2002 wall seam was the simplest construction to manufacture; as a

result, the more exotic seam concepts were dropped moving forward and all shelters used the standard M2002 wall seam. The most significant change to the CHIEFS concepts moving

forward from the September 2016 tests was the loss of the baseline polytetrafluoroethylene (PTFE) gas barrier laminate.

The baseline gas barrier layer (inner most layer to the shelter interior of the shelter wall) for Gen 2 CHIEFS shelters was a fiberglass reinforced PTFE laminate. This laminate is described in greater detail in previous work by Fody, et. al. [5]. The PTFE gas barrier provided significant improvement to the M2002 standard gas barrier due to its ability to remain impermeable up to wall temperatures approaching 500°C (932°F) (determined by measuring mass loss upon exposure to heating in a furnace) compared to the M2002 gas barrier which fully delaminates at temperatures less than 400°C (752°F) (determined by observing samples exposed to temperatures in an oven for two minutes). Tests in September 2016 showed that there was a 24% increase in duration of habitability with CHIEFS shelters using the PTFE gas barrier compared with equivalent CHIEFS shelters using the standard M2002 gas barrier. However, the USFS eliminated the use of the PTFE gas barrier due to concerns about possible deleterious decomposition byproducts being released into the shelter interior upon heating. With this elimination, the CHIEFS effort had no readily available alternative apart from the M2002 gas barrier. CHIEFS shelters using the M2002 gas barrier exhibited only a 28% improvement in habitability compared with the current M2002 shelter (compared with 86% in the best performer using PTFE); consequently, an effort to find a suitable replacement gas barrier commenced.

PTFE Gas Barrier Replacement and Close-Out Full Scale Shelter Development

Much of the 2017 fiscal year was spent investigating potential replacements for the PTFE gas barrier that exhibited improved performance relative to the M2002 gas barrier. Various novel methods of directly bonding aluminum to fiberglass fabric investigated included hot pressing, hot rolling, coating the fabric in molten aluminum, and creative ways to use ultrasonic welding to secure aluminum foils to the fiberglass. Additionally, CHIEFS began screening various adhesives with high temperature tolerance relative to the adhesive used in the M2002 gas barrier. Ultimately, the adhesive approach, not direct bonding, proved to be most commercial ready and a polyimide adhesive produced by Imi-Tech Corporation was procured. Panels were laminated with the Imi-Tech adhesive at NASA Langley Research Center using the same fiberglass fabric and aluminum foil as the M2002 gas barrier; these panels were used to fabricate full scale shelters and included in testing at the University of Alberta in April 2017.

Shelter performance during the April 2017 test was generally unimpressive with several shelters exhibiting similar durations of habitability as the M2002. The baseline shelter concept, which used the “PDS3” layup with a standard M2002 gas barrier, was among the top performers exhibiting a habitability about 28% better than the M2002, consistent with a similar shelter tested in September 2016 using the same gas barrier. The MW shelter tested exhibited about average thermal performance for the CHIEFS designs tested (12% improvement in habitability compared with the M2002). Additionally, the USFS raised concern over the shelters tendency to collapse inward during heating and decrease the internal volume and consequently breathing air available. As the MW shelter would need additional manufacturing development to be a practical design to carry forward, it was abandoned for future tests with the idea that it might be picked up again in the future.

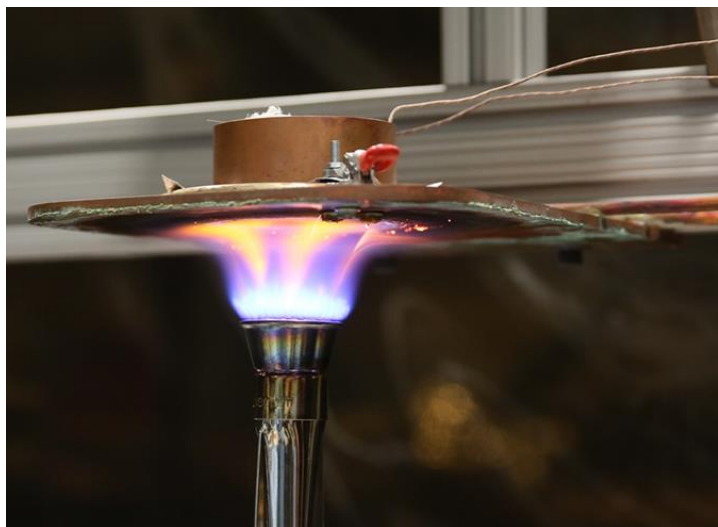
An inverted (foil facing outward toward the heat source) standard M2002 gas barrier exhibited surprisingly good post-test material conditions. Large concentrations of combustible byproducts were injected into the shelter interior upon thermal failure of the standard M2002 laminate adhesive which resulted in significant combustion early in the test; however, the

temperature plot of the shelter interior prior to the combustion showed promise. The shelters with the Imi-Tech polyimide adhesive (installed in the normal foil inward configuration) performed relatively well thermally and the adhesive remained intact longer than the M2002 gas barriers tested in the same orientation. It was also apparent that the polyimide adhesive decomposed into less combustible volatiles than the standard M2002; however, carbon monoxide levels were high. In an effort to zero in on an enhanced gas barrier concept, an inverted M2002 laminate using the polyimide adhesive (inverted laminate) was carried forward to CHIEFS close-out shelter testing.

This writing will now focus on tests conducted at the University of Alberta in August and September 2017, as well as small scale tests of samples of the same layups conducted at NASA Langley Research Center. Shelters tested were variants of the successful “PDS3” layup carried forward from the September 2016 tests, which replaced the PTFE gas barrier with a novel concept which includes the inverted laminate described above. At the conclusion of fiscal year 2017, CHIEFS failed to secure continued funding into fiscal year 2018 (the October tests had already been funded); therefore, these tests are now considered “close-out shelters” and are the final concepts produced by NASA’s CHIEFS effort.

Small-Scale Convective Test Setup

The CHIEFS small-scale test apparatus was the primary test setup used to perform testing on candidate material layups being considered for full scale shelter development. The design is a modified version of the setup used by the U.S. Forest Service [7, 8, 9, 10, 11]. The CHIEFS small-scale setup is shown in Figure 3, and consists of a cylindrical copper cup that



contains the test sample, attached to a water cooled copper plate, and a Meker burner. The Meker burner is very similar to the Bunsen burner; however, its flame structure is an aggregate of small cones (rather than one large cone as in a Bunsen burner) and heating is distributed more evenly across the test sample surface. When testing, the flame is first calibrated to a cold wall heat flux of $8 \pm 0.4 \text{ W/cm}^2$ using a copper disc calorimeter before test samples are exposed to heating.

FIGURE 3: CHIEFS SMALL SCALE CONVECTIVE TEST SETUP.

The test sample which consists of an outer shell material, insulation layers, and an inner gas barrier is installed in the cylindrical cup. The outer shell faces down toward the flame. A 5.1 cm (2 inch) thick loose fill alumina fiber batting is placed on the backside of the gas barrier (above the sample) to produce a quasi-adiabatic backside boundary condition. Two thermocouples are typically installed on the backside of the gas barrier and their average value used. The sample is exposed to the calibrated flame, and the transient thermocouple response on the gas barrier is recorded and analyzed in order to make decisions about material selection and placement within the layups. A post-test calibration is also performed in order to ensure that exposure heat flux did not deviate drastically from the initial calibration level during the test. A schematic of the small scale test setup is shown in Figure 4.

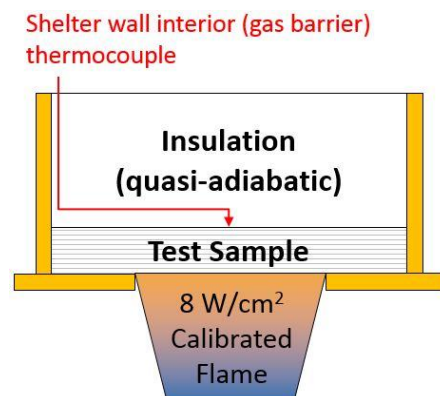


FIGURE 4: SMALL SCALE CONVECTIVE TEST SETUP SCHEMATIC.

Full Scale Shelter Test Setup



FIGURE 5: FULL SCALE SHELTER TEST APPARATUS WITHOUT ENCLOSURE. INSTRUMENTATION (TOP), AND DEPLOYED TEST ARTICLE (BOTTOM).

The August and October 2017 full scale tests were conducted at the University of Alberta's Protective Clothing and Equipment Research Facility (PCERF) satellite laboratory in Edmonton, Alberta, Canada. The facility is contracted by the USFS MDTC to conduct testing in support of their fire shelter revision. All official test data on full scale candidate fire shelters, which may be selected to replace the M2002 by the USFS, was generated at this facility. A photograph of the test setup is shown in Figure 5. The top photograph shows the instrumentation to be positioned inside of the shelter, shown on its side, once the shelter was placed flat on the test bed. The bottom photograph shows the shelter in position for testing, and eight propane torches oriented around the perimeter of the shelter.

The fire shelter is positioned on a flat-bed test stand built onto a mobile trailer so that it may be placed outdoors. The bed of the test stand is covered in a continuous layer of approximately 2.5 cm (1 inch) thick alumina fiber batting. The propane torches located around the periphery of the bed, and the openings in the edges of the bed around the torches allowing the flames into the interior, are shown in the lower figure. There are eight torches: one at the head, one at the foot, and three evenly spaced along both sides of the test bed. A galvanized steel enclosure is placed

over the shelter prior to testing so that flames are confined close to the shelter wall. A photograph of the test rig with enclosure installed and torches active is shown in Figure 6.

A shelter frame was used for all close-out shelter tests. The frame was constructed of approximately 1/4-inch x 1/4-inch steel bar bent into a basic structure and closely fit the inside of the shelter; however, the design was intended to prevent tight contact and compression of the shelter walls. The frame was covered in strips of alumina batting to prevent direct contact of hot bare metal with the wall material. The purpose of the frame was to keep the shelter propped up into a consistent full shape so as to ensure consistent internal volume and shelter wall dimensions between tests. The framework was relatively thin and not expected to significantly impact thermal conditions inside the shelter.

All CHIEFS shelters were constructed with a “racetrack” floor. The racetrack floor was a 6-inch band of floor material that ran around the outside of the shelter wall, lying flat on the test bed, rather than the conventional internal floor (a “racetrack” running around the inside, that the firefighter uses to hold the shelter down to the ground). Standard M2002 shelters tested were manufactured with the standard internal floor; in these shelters the internal floor was cut radially on regular intervals so that the floor material could be folded outward to mimic the exterior racetrack design. Strips of 1-inch thick alumina fiber batting were placed around the shelter perimeter, on top of the external floor material, and a heavy chain was placed around the periphery of the shelter floor band on top of the alumina batting. The purpose of the chain and insulation was to keep the shelter tight against the test bed floor and prevent flame ingress into the shelter from underneath, and having the shelter floor on the exterior of the shelter allowed easy access for placement of the chain and alumina batting. By preventing flame ingress into the shelter from underneath, wall materials performance could be isolated and compared between shelters. It was generally assumed that ground conditions at a given site in a real fire shelter deployment would be the driving factor influencing any flame ingress from underneath the floor bands, and terrain can vary wildly. Such variations in terrain, fire behavior at the ground level, and the orientation and size of the firefighter inside the shelter holding the floor material down to the ground would contribute to variation in a real shelter deployment but would be impossible to account for in a repeatable laboratory test. Additionally, without the use of the exterior racetrack floor, chains, and insulation, slight variations in the placement of the shelter in the laboratory test bed introduces confounding variability in the amount of flame ingress from under the floor band to the shelter interior making it difficult to isolate the effect of a candidate shelter’s material design on overall test performance.

Two thermocouple trees were mounted on the flat-bed test stand close to the location where the head of a firefighter would be positioned during an actual deployment (approximately 25.4 cm (12 inches) from the heated head end of the shelter), and in approximately the same location at the foot of the shelter. Two thermocouples were installed on this tree, at heights of 5.1 and 25.4 cm (2 and 10 inches) above floor level. The 5.1 cm (2 inch) thermocouple represents the temperature associated with the breathing zone of the fire fighter and was the most critical measurement during these tests. Limits of human survivability for breathing air are assumed by the Forest Service to be temperatures of approximately 150°C; so, the main evaluation criteria for shelter testing is to determine the elapsed time until the 5.1 cm (2 inch) thermocouple exceeds 150°C. It should be noted that since the heating is approximately symmetric in the test bed, 2-inch and 10-inch temperature data reported is an average of the “head” and “foot” thermocouples in the shelter. Shelters were tested until either the cooler of the two 2-inch thermocouples exceeded 150°C or 120 seconds of testing had elapsed (whichever occurred first). Structural components on the test bed limit the shelter test duration to 120 seconds maximum; however, tests are usually terminated due to the two 2-inch thermocouples limit so tests typically do not reach 120 seconds in duration. Close-out shelter tests often did reach the 120 second mark – tests limited by hardware limits rather than shelter failure – but this phenomenon was rarely observed in any previous testing conducted by the USFS including previous NASA CHIEFS shelters.

Copper disk calorimeters, the same type that was used in the small-scale convective test setup calibrations, were embedded into boxes on the shelter floor with the copper disk facing upward so as to measure an estimate of the total heat flux incident on the shelter floor. Two boxes were located in the test bed, one near each of the two thermocouple trees described above, and can also be seen in Figure 5. The boxes had a flat horizontally level top, with angled sides facing approximately 45° from the top. One calorimeter was placed in the center of each of the three surfaces of the box, one flat horizontal and two on 45° angled sides, in both boxes (total of six sensors). The calorimeters were intended to primarily approximate the level of thermal radiation a firefighter would be subjected to inside of the shelter; however, some convective heating must also be contributing to the measurement. The six sensors were averaged when internal heat flux is reported for the tests.

Gas sampling ports were located in the test bed near the location of one of the copper calorimeter boxes near the shelter end. Shelter interior gas composition was analyzed by two methods. First, oxygen, carbon dioxide, and carbon monoxide were analyzed using a California Analytical instrument which provided continuous data sampling from a constantly streaming



FIGURE 6: FULL SCALE SHELTER TEST APPARATUS AT THE UNIVERSITY OF ALBERTA WITH FLAMES ON DURING TESTS.

sample. The sample for the first method traveled through a small diameter clear polymer tube spanning approximately 5.1 m (20 feet) between the instrument and the gas port; consequently, there was a lag of about 20 seconds between reported temperatures and reported gas composition from the first method. The second method of gas composition analysis was used only occasionally. Immediately after heating was terminated, a vacuum pump was activated which pulled a gas sample from one of the ports in the test enclosure into a grab bag located some 2.5 m (10 feet) away from the test enclosure. The contents of this grab bag were intended to contain the mixture of decomposition byproducts produced by the various shelter materials during heating. This grab bag was sent off to an independent laboratory where a capillary gas chromatograph-mass selective detector was used to compare spectral data to a library of known compounds for best guess identification of constituents. This method has some limitations, not the least of which is that samples are obtained at the conclusion of the test after wall materials have been structurally compromised and the internal atmosphere may be able to ventilate freely to the external environment. As a result, the analysis does not give a good indication of the compounds that a firefighter may be exposed to in the event that an actual shelter deployment does not endure long enough to reach the point of failure (the point at which a firefighter would no longer survive, as determined by the thermal test termination criterion). This method does, however, provide some indication of potentially toxic compounds that may be produced by a tested shelter under certain conditions.

The heat flux inside the enclosure was measured with two Medtherm Schmidt-Boelter type heat flux calorimeters (model 64-20T-20R(S)-21210). The Medtherm sensors each had two non-cooled Schmidt-Boelter calorimeters, one positioned behind a sapphire window in order to measure the radiant portion of incident heat. By subtracting the measured radiant portion of the heat flux from the total heat flux measured by the second calorimeter, the convective component could be estimated. There is some concern about the accuracy of the radiant data due to the portion of the infrared spectrum in which the sapphire is transparent; thus, the total heat flux measurement was predominantly used. The devices were placed inside the metal enclosure, one near the shelter head and one near the foot, and faced in toward the test article.

Finally, one or two video cameras were placed inside of the fire shelter during testing. The cameras were placed in insulated boxes placed near the copper calorimeter heat flux boxes. Each camera faced toward the opposite end of the shelter. The video images provided useful visual data on the conditions inside the shelter including apparent smoke density, presence of flaming or flashing, points of smoke or flame ingress, and material conditions throughout the test such as charring, cracking, delamination, or sagging of wall materials.

Close-out Shelter Layups

The first generation, Gen 1, CHIEFS shelters were mainly designed to increase convective thermal performance with an emphasis on keeping mass as low as possible. In addition to convective thermal performance and mass, Gen 2 efforts targeted shelter packed

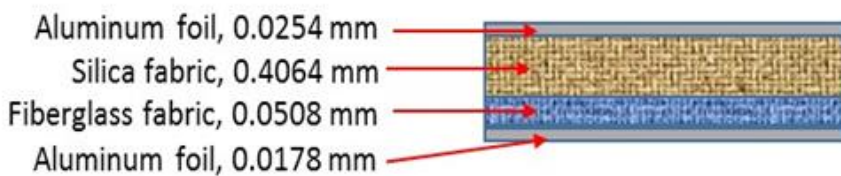


FIGURE 7: LAYUP OF CURRENT M2002 SHELTER.

volume, cost, toxicity of decomposition byproducts, durability, and ease of manufacturing. The shelters developed for the March 2016 test series used the standard M2002

geometry and targeted layups with areal masses not to exceed 15% of the areal mass of the M2002 shelter (less than or equal to 0.4 g/in^2 (18.3 oz/yd^2)). As a result, many successful Gen 1 materials were abandoned, and new materials were introduced.

The existing M2002 shelter layup is shown in Figure 7. The outer shell consists of a 0.4064 mm (0.016 in) thick silica fabric at 0.208 g/in^2 (9.5 oz/yd^2) laminated by Custom Laminating Corp. (Mt. Bethel, PA) to a 0.0254 mm (0.001 in) thick aluminum foil using a proprietary water based adhesive. The outer shell is installed on the shelter with the aluminum foil facing outward. The inner layup consists of a 0.0508 mm (0.002 in) thick fiberglass fabric with an areal mass of 0.030 g/in^2 (1.38 oz/yd^2) laminated to a 0.0178 mm (0.0007 in) layer of aluminum foil using the same adhesive, also from Custom Laminating Corp. The inner shell is installed on the M2002 such that the aluminum foil faces the shelter interior. The overall thickness of the shelter wall is 0.5004 mm (0.0197 in) with an overall areal mass of 0.34 g/in^2 (15.5 oz/yd^2). The overall shelter with the floor band, seams, and straps weighs 1.95 kg (4.30 lb) and has a packed volume of approximately 3441 cm^3 (210 in^3). The shelter is 218 cm (86 inch) long, 39.4 cm (15.5 in) high, and 78.7 cm (31 in) wide when deployed. A photograph of fully deployed M2002 shelter is shown in Figure 8.



FIGURE 8: EXISTING FIRE SHELTER (M2002) [12].

Various gas barrier materials were investigated by CHIEFS to see if lighter options, with improved thermal performance, and lower cost – relative to the first generation gas barriers – could be identified. The first and second generation shelter gas barrier was a PTFE-fiberglass fabric laminate with an areal mass of 0.085 g/in^2 (3.89 oz/yd^2). After the completion of full scale shelter testing at the University of Alberta in September 2016, the USFS eliminated the use of the PTFE gas barrier due to concerns about possible deleterious decomposition byproducts being

released into the shelter interior upon heating.

A primary focus of the CHIEFS effort during the 2017 fiscal year was to identify a suitable replacement gas barrier to the baseline PTFE laminate; several concepts were investigated including a fiberglass-aluminum foil laminate fabricated using a high temperature polyimide adhesive and an inverted standard M2002 gas barrier. Ultimately, a hybrid of these two concepts was carried forward: an inverted (foil facing outward toward the heat source) M2002 gas barrier which used the polyimide adhesive. The inverted laminate was constructed of a fiberglass fabric and aluminum foil very similar to the existing M2002 inner liner except for the use of a high temperature polyimide adhesive. The inverted laminate was installed in the fire shelter layup in reverse orientation to the current M2002 inner liner with the aluminum foil facing outward away from the shelter interior. The inverted orientation demonstrated significantly improved thermal performance, likely due to three factors. First, the higher failure temperature of the polyimide adhesive and, second, the inverted orientation of the laminate kept the aluminum foil intact and in place longer than the M2002 inner liner which typically exhibited large scale delamination with sections of the aluminum falling into the shelter immediately followed by a large spike in interior air temperature. Keeping the aluminum intact and in place longer likely worked to minimize bulk gas advection through the highly permeable insulations in more outward layers of the shelter wall layup. The third factor likely benefitting the inverted laminate is that placing the aluminum closer to the heat source, rather than closer to the shelter

interior, took advantage of aluminum's high radiant reflectivity and likely worked to protect the underlying adhesive and fiberglass fabric. The major disadvantage of this inverted laminate was that upon failure of the polyimide adhesive, large amounts of visible smoke and measured carbon monoxide gas (as well as a variety of other constituents) were released directly into the shelter interior. As a result, the inverted laminate was not deemed to be viable in its original form, but the addition of an aluminized polyimide film (aluminized Kapton) beneath (interior of) the inverted laminate (aluminized surface also facing outward toward the heat source) was proposed to mitigate the release of these undesirable byproducts and provide additional capacity to inhibit gas advection and reduce radiant heat transmission toward the shelter interior. This binary gas barrier system was carried forward for testing in the currently described close-out shelter layups.

The binary system consisted of the inverted laminate installed (aluminum facing outward) above (outward of) a layer of aluminized Kapton (aluminized surface facing outward). The inverted laminate was composed of a layer of 1235 series anodized aluminum foil 0.02 mm thick (.00079 inch), adhered to a layer of 1080 denier fiberglass fabric coated with a silane sizing at 0.0508 mm (0.002 in), using a proprietary polyimide adhesive supplied by Maverick Corporation. Maverick Corporation performed the laminating work as well. The areal mass of the laminate was 0.067 g/in² (3.1 oz/yd²), and its thickness was 0.220 mm (0.009 inch). Additionally, a variation of this inverted layup was tested using a layer of 1100 series aluminum foil 0.018 mm thick (.0007 inch), adhered to a layer of 1080 denier fiberglass fabric at 0.0508 mm (0.002 in), using a proprietary silicone based adhesive supplied by Custom Laminating Corporation. Custom Laminating Corporation also performed the laminating work on this layup. The areal mass of the laminate was 0.070 g/in² (3.2 oz/yd²), and its thickness was 0.085 mm (0.003 inch). This silicone adhesive laminate had been tested in the past by the USFS, and had been rejected due to a significant buildup of white powder on the shelter interior test bed, possibly colloidal silica, upon failure of the adhesive. However, the silicone adhesive was desirable for three reasons: it was produced by a company which already has a good working relationship with the USFS, it is more durable and flexible at room temperature than the polyimide adhesive laminate from Maverick Corporation (in its current form), and it is likely a much cheaper material and cheaper laminating process. It was suspected that adding the aluminized Kapton layer might prevent the white powder from reaching the shelter interior. Although the adhesive had previously been rejected and it was known that the adhesive would have a lower thermal failure point than the polyimide adhesive, it was carried forward as one design alternative in the close-out tests. In all of the above configurations, the aluminized Kapton layer used was a 0.05 mm (0.002 inch) thick polyimide film aluminized on one side and supplied by Dunmore Corporation (product number DE330).

The CHIEFS close-out shelters used two similar versions of laminate for the outer shell. The most common version was composed of a 0.122 g/in^2 (5.6 oz/yd^2) silica fabric with a 0.0254 mm (.001 inch) thick aluminum fabric bonded to it by Custom Laminating Corporation using the same proprietary adhesive that is used on the M2002. The areal mass of this laminate, known as the “single 7” (S7), is 0.164 g/in^2 (7.5 oz/yd^2), and its thickness is 0.305 mm (0.012 inch). There was also an alternate version tested which used the same 0.122 g/in^2 (5.6 oz/yd^2) silica fabric but with a 0.0254 mm (.001 inch) thick anodized 1235 series aluminum fabric bonded to it by Maverick Corporation using their proprietary polyimide adhesive. The areal mass of this alternate laminate was approximately 0.198 g/in^2 (9 oz/yd^2), and its thickness was 0.330 mm (0.013 inch); however, the adhesive content varied significantly as the manufacturer worked to find a good balance between adhesion and flexibility. Both layups are reduced mass concepts



FIGURE 9: UAI FIBERGLASS INSULATION BATTING.

compared to the standard M2002 outer shell, 0.262 g/in^2 (12 oz/yd^2), and by removing mass from the outer shell fabric, which is likely mechanically overbuilt, this mass could be used where it would have a more effective contribution to thermal performance in the form of insulations. The purpose of testing the alternate version, with the polyimide adhesive, was that it was suspected that fewer flammable decomposition compounds would be produced by the polyimide adhesive compared with the standard M2002 adhesive; therefore, by potentially minimizing the injection of hot gasses into the shelter wall insulations, material degradation and overall heat transfer to the shelter interior may be delayed.

Various insulations were investigated for placement between the outer and inner shelter layers during the CHIEFS Gen 1 and Gen 2 efforts. These insulations are covered in some detail in previous work [5, 6]. At the conclusion of the Gen 2 effort, a fiberglass batting insulation produced by UPF Corporation was found to meet most of the requirements for fire shelter application. These soft and light weight battings are referred to as Ultracore Aircraft Insulation (UAI) and are produced in layers with densities between 5.4 and 10.9 kg/m^3 (0.34 to 0.68 lb/ft^3) and areal densities of 0.045 to 0.055 g/in^2 (2.1 to 2.5 oz/yd^2). The insulation battings have a nominal thickness of 12.7 mm (0.5 inch), but are highly compressible and were shown in CHIEFS tests to retain existing thermal performance after being compressed to approximately 9.5 psi for several days at a time. Furthermore the fiber is extremely flexible and foldable, and is commercially available as insulation used on commercial passenger aircraft. Mass spectrometry and thermogravimetric analysis measurements were conducted on this UAI insulation at NASA Langley Research Center up to 1000°C at a rate of 20°C per minute, and confirmed the absence of toxic byproducts. A photograph of a sample of this insulation is shown in Figure 9. As in the CHIEFS Gen 2 designs, graphite intumescent flakes were sourced from Asbury Carbons (Asbury, NJ) and, imbedded into the fiberglass batting by UPF Corporation. Furthermore, UPF Corporation succeeded in adding a coarse fiberglass scrim, into the insulation. This scrim was requested by the USFS as a measure aimed at producing a more durable insulation better suited to the rigors of use in the field. The UAI insulation with only the graphite used fiberglass batting with a density of 5.4 kg/m^3 (0.34 lb/ft^3), the insulation

with only scrim used fiberglass batting with a density of 10.9 kg/m³ (0.68 lb/ft³), and the insulation with both graphite and scrim used fiberglass batting with a density of 5.4 kg/m³ (0.34 lb/ft³). A picture of the UAI insulation with imbedded graphite intumescent flakes and scrim is shown in Figure 10.



FIGURE 10: UAI FIBERGLASS INSULATION WITH EMBEDDED INTUMESCENT GRAPHITE FLAKES AND SCRIM.

Gen 2 testing conducted at North Carolina State University in the summer of 2016 indicated that an insulation configuration which uses two layers of UAI separated by a thin polymer film, with the outer most layer of UAI insulation containing imbedded intumescent graphite flakes, exhibited top thermal performance relative to other tested options [5]. This configuration was carried forward to full scale testing at the University of Alberta in September 2016 where it was determined that the same layup without the thin polymer film separating UAI layers exhibited better performance than with the polymer film. For this reason, the internal polymer film layer was dropped, and this double layer UAI configuration was carrier forward as a baseline. The CHIEFS close-out shelters continued with this baseline, except for the

modification that a layer of scrim was added to the inner most layer of UAI (without the graphite intumescent flakes). A single layer UAI version was also tested, as a lighter weight alternative; in this configuration, the single UAI layer contained both the intumescent graphite flakes and scrim. The CHIEFS close-out layups tested are summarized graphically in Figure 11.

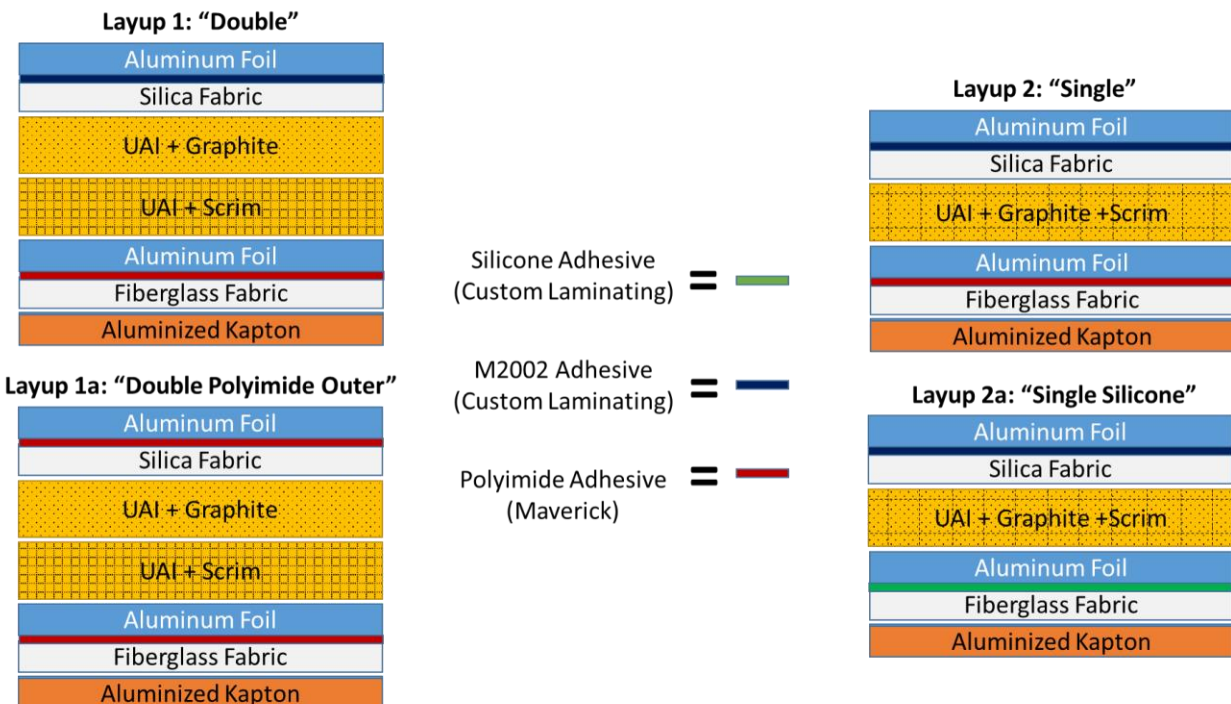


FIGURE 11: GRAPHICAL DEPICTION OF CHIEFS CLOSE-OUT SHELTER LAYUPS.

The various layups and their associated areal mass and compressed thickness are listed in Table 1. The thickness reported in the table was obtained using an Ames Gauge, which applies compression pressure to a 6.45 cm² (1 in²) round foot, and is commonly used to measure thickness in compressible textiles; the pressure applied for these measurements was 2.2 kPa (0.313 lbf/in²).

TABLE 1: LAYUPS TESTED IN FULL SCALE CLOSE-OUT SHELTER TESTS

Layup Number	Layup Name	Areal Mass		Compressed Thickness	
		g/m ²	Oz/yd ²	cm	inch
	M2002	498	14.7	0.076	0.030
1	Double	658	19.4	0.831	0.327
2	Double Polyimide Outer	709	20.9	0.833	0.328
3	Single	573	16.9	0.333	0.131
4	Single Silicone	570	16.8	0.259	0.102

Full Scale Close-Out Shelters

Full scale close-out fire shelters were tested over two test campaigns: one in late August 2017 and the other in late October 2017. Several standard M2002 shelters were tested on both dates; the M2002 serves as the baseline for comparison of shelter performance. Additionally, there were four CHIEFS shelter concepts tested based solely on the four layup configurations described in Table 1. In August, the “Double” and “Double Polyimide Outer” concepts were tested; there were three of each configuration tested for a total of six CHIEFS shelters in addition to two M2002s. In October, the “Double”, “Single”, and “Single Silicone” concepts were tested; there were two of each configuration tested for a total of six CHIEFS shelters in addition to four M2002s. In total, twelve CHIEFS shelters and six M2002s were tested during the fall of 2017. Unlike several previous CHIEFS tests, including the testing at NCSU [5], the majority of the close-out CHIEFS shelters were fabricated exactly the same except for the wall layup materials. The only exception was the full floor which was installed on

TABLE 2: FIVE SECOND GENERATION SCREENING TEST SHELTERS

Layup Name	Average Shelter Mass [lb]	Floor	Test Date	Shelters Tested
M2002	4.3	Full	August	2
Double	4.9	Racetrack	August	3
Double Polyimide Outer	5.3*	Full*	August	3
M2002	4.3	Full	October	4
Double	4.9	Racetrack	October	2
Single	4.6	Racetrack	October	2
Single Silicone	4.5	Racetrack	October	2

the “Double Polyimide Outer” shelters by mistake. This variation would have no effect on the data reported in this paper; however, the shelter mass is slightly higher than if a racetrack floor would have been used, and consequently a direct comparison to the mass of the “Double” is not accurate. All shelters used the standard M2002 geometry, M2002 wall seams, racetrack floor (described in more detail in the “Full Scale Shelter Test Setup” section), and M2002 floor band seams. Total shelter mass for each concept tested and the test dates are shown in Table 2. It should be noted that actual production shelters, for the CHIEFS concepts, would be a few tenths of a pound heavier than the reported values here because a full sized floor as well as deployment handles would be required.

Full Scale Shelter Test Criterion

Shelters were tested until either the cooler of the two 2-inch thermocouples exceeded 150°C or 120 seconds of testing had elapsed (whichever occurred first). The 120 second cut off was the result of a need to limit the duration that the test apparatus was exposed to heating, and the 150°C 2-inch thermocouple cut off was selected as the 2-inch thermocouple temperature fail point. Shelter conditions beyond the limits of habitability were not sought. Close-out shelter tests were graded by comparing time to failure. Failure was meant to approximate when conditions inside the shelter were expected to no longer be survivable. Time to failure occurred when at least one of six variables exceeded a limit; five of these variables are described in Table 3, the sixth variable being the observation of significant heavy smoke particles or irritants inside of the shelter post-test or in video data. The cut off values were selected by the USFS and University of Alberta test directors. The selected values give some basis for comparison between shelter candidates. Rationale for each variable is described in more detail in the paragraph below.

A 1944 study conducted on the injuries sustained by animals inhaling heat is the basis for the 2-inch “breathing zone” temperature criterion limit. In the study, 18 dogs and 2 pigs were

TABLE 3: FIVE OF SIX SHELTER TEST FAILURE CRITERION.

Variable	Failure Criterion	Rationale	Justification
2-inch Thermocouple	> 150°C	Breathing Air Temperature	[13]
10-inch Thermocouple	> 300°C	NFPA 1977 Gear Limits	[14]
Internal Heat Flux	> 2 W/cm ²	Radiant 2 nd Degree Burns	[15, 16]
Carbon Dioxide Level	> 1700 parts/million	Dangerous @ 10 min.	[17]
Oxygen Level	< 10%	Impaired Judgement	[18]

subjected to direct injections of dry air, steam, and flames at various temperatures. The animals were sedated for the study; all but two animals were killed and autopsy revealed the extent of damage. The author describes a key finding, “A few breaths of air delivered into the pharynx at a temperature of 300°C or of steam delivered at 100°C caused such severe local edema within a few hours that the animals died of obstructive asphyxia.” A value of 150°C was selected by the test directors as a reasonable maximum survivable limit.

The 10-inch thermocouple maximum temperature limit was selected based on the requirements of NFPA 1977 [14], a standard which dictates performance requirements for protective equipment carried by fire fighters. The National Fire Protections Association (NFPA) publishes a variety of standards which regulate the fire protection industry. NFPA 1977 requires

that materials used in protective gear commonly carried by wildland fire fighters, such as hard hats and backpacks, must pass a 260°C oven exposure test. A value of 300°C was selected by the test directors as a reasonable maximum limit.

Maximum internal radiant heat flux exposure was estimated using criterion developed by Alice Stoll. Stoll was involved in several studies which sought to measure the radiant heat flux exposure required to deliver a 2nd degree burn to bare skin [15, 16]. Stoll criterion are well established in the fire protection industry and the gold standard Thermal Protective Performance (TPP) metric is based on values generated from Stoll criterion. Stoll's work assessed bare skin exposed to heat; but, firefighters would be clothed in protective gear in a shelter deployment and can tolerate a higher heat flux. Unpublished research conducted at the University of Alberta indicates that, if bare skin is covered by typical firefighter protective garments, a second degree burn (according to Stoll criterion) would be realized after approximately 25 to 35 seconds for an incident exposure of 2 W/cm² or greater. The test directors selected this 2 W/cm² exposure value as the failure criterion for the incident radiant exposure. Failing the test at 2 W/cm² means the exposure throughout the test was below this value; however, the Stoll criterion must assume a constant, not varying, heat flux exposure level to predict time to burn injury. Consequently, the test directors decided to use the criterion as guidance only, and ultimately felt that the 2 W/cm² limit provided a satisfactory safety margin.

Acute Exposure Guidelines Levels (AEGLs) are publically available for carbon monoxide by the Environmental Protection Agency. AEGLs for carbon monoxide range from 1 to 3, with 3 being the most extreme exposure. Level 3 for carbon monoxide is associated with a lethal level of poisoning. According to AEGL-3, carbon monoxide is lethal in 10 minutes at a concentration of 1700 parts/million. This value was selected for the failure criterion for carbon monoxide by the test directors; however, they note that this value may be too lenient due to stricter estimates from other published sources.

The United States Occupational Safety and Health Administration (OSHA) Respiratory Protection Standards 1910 and 1926 were the basis of the minimum oxygen criterion selected for the tests. Test directors reference the standards indicating that oxygen levels of 10-14% results in impaired judgement. Less than 10% oxygen concentration results in more severe reactions. A value of 10% was selected by the test directors as the minimum oxygen concentration of a survivable shelter interior.

Full Scale Shelter Test Results

Shelters in the August test performed very well exhibiting by far the best performance of all CHIEFS shelters tested to date which had a similar mass to the M2002. The Double shelter reached the 120 second maximum test time without failing any of the six test criterion. NASA tested a Gen 1 CHIEFS shelter concept, "M2002-Heavy" in September of 2015, which had similar thermal performance on the 2-inch thermocouple to the Double close-out shelter; however, the M2002-Heavy weighed 8 lb (3.6 kg), an increase of 63% compared with the Double, and was considerably bulkier. Furthermore, Gen 1 shelters tested in September 2015 commonly exhibited significant internal flashing or other combustion, which was true in both M2002-Heavy shelters tested. None of the close-out shelters tested in either the August or the October tests exhibited any significant internal combustion. As a result, the close-out shelters are considered the most successful of the CHIEFS shelters tested.

Shelters were exposed to heating from eight propane burners inside a galvanized sheet metal enclosure. In general heating was similar between the August and the October tests;

however, there was a significant range in heat flux exposure between individual shelters (approximately +/- 20% from the average at a given time). The total measured heat flux for all shelters tested, segregated by test dates, are shown in Figure 12. Medtherm gauges were placed in two corners of the test bed, external to the fire shelters, and faced inward toward the center where the fire shelter was located. The gauges were not water cooled which may introduce error. Data shown here seems to indicate increasing heat flux during the first half of the test, and then a leveling off toward the last half. It is unclear if or how these trends may be effected by either a warming cold side temperature reference in the non-cooled heat flux gauges, or an accumulation of high absorptivity carbon (soot) on the sensor faces during the test, or the changing thermodynamics of the shelter interior due to heating of the enclosure shroud and degradation and heating of the shelter, or changes in the stoichiometry of the combusting propane throughout the tests. Results for close-out shelter tests will be reviewed next for both August and October tests by failure criterion variable performance.

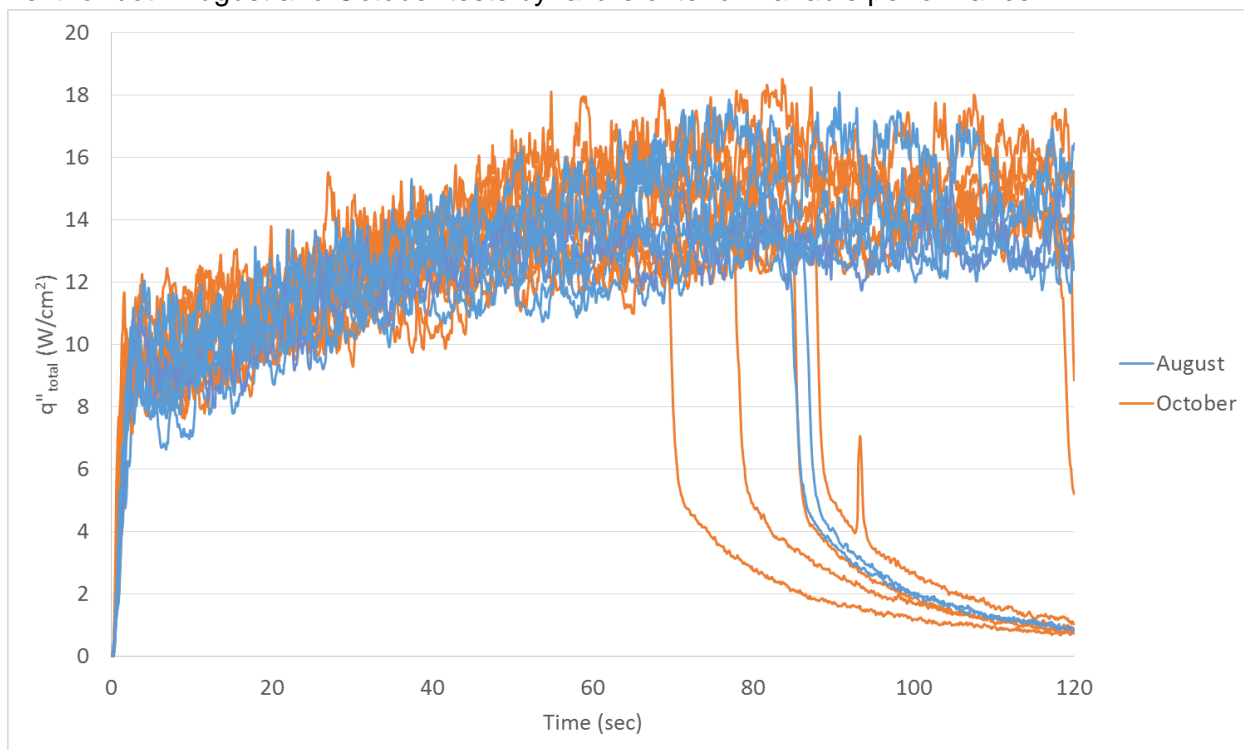


FIGURE 12: AVERAGE TOTAL HEAT FLUX OUTSIDE OF SHELTERS RECORDED BY MEDTHERM SENSORS FOR ALL TESTS.

Performance at the 2-inch “breathing zone” thermocouple followed expected trends between CHIEFS shelters and is shown in Figure 13. The data shown is the average of all shelters tested within a given design, as well as the average of both 2-inch thermocouple results for each individual shelter. In both test series, CHIEFS shelters significantly outperformed the M2002. Between CHIEFS shelters, the Double shelter offered the best performance (longest duration of “habitable” breathing zone temperatures), followed by the lighter and thinner Single shelter, and finally followed by the M2002. The variations tested (Double Polyimide Outer and Single Silicone) did not indicate significant performance differences compared with the Double and Single standard shelters respectively; however, there is some indication that both variations performed slightly worse than their respective baseline designs in both cases. No Double design failed the 2-in thermocouple criterion prior to the 120 second test cut off; however, by using linear extrapolation the Double shelters offered approximately a 100% improvement in the

duration of habitability compared to the M2002 for this variable. The Single shelters performed about 56% better. Outdoor testing in Edmonton in October was significantly colder than in August, which is evident in the temperatures at the start of heating between tests. In addition to the difference in starting temperature, the difference in the slope of the linear portion of the temperature rise in the Double shelters tested in August is lower than in the October test. Double shelters in both tests were physically the same, and heat flux was comparable as demonstrated above.

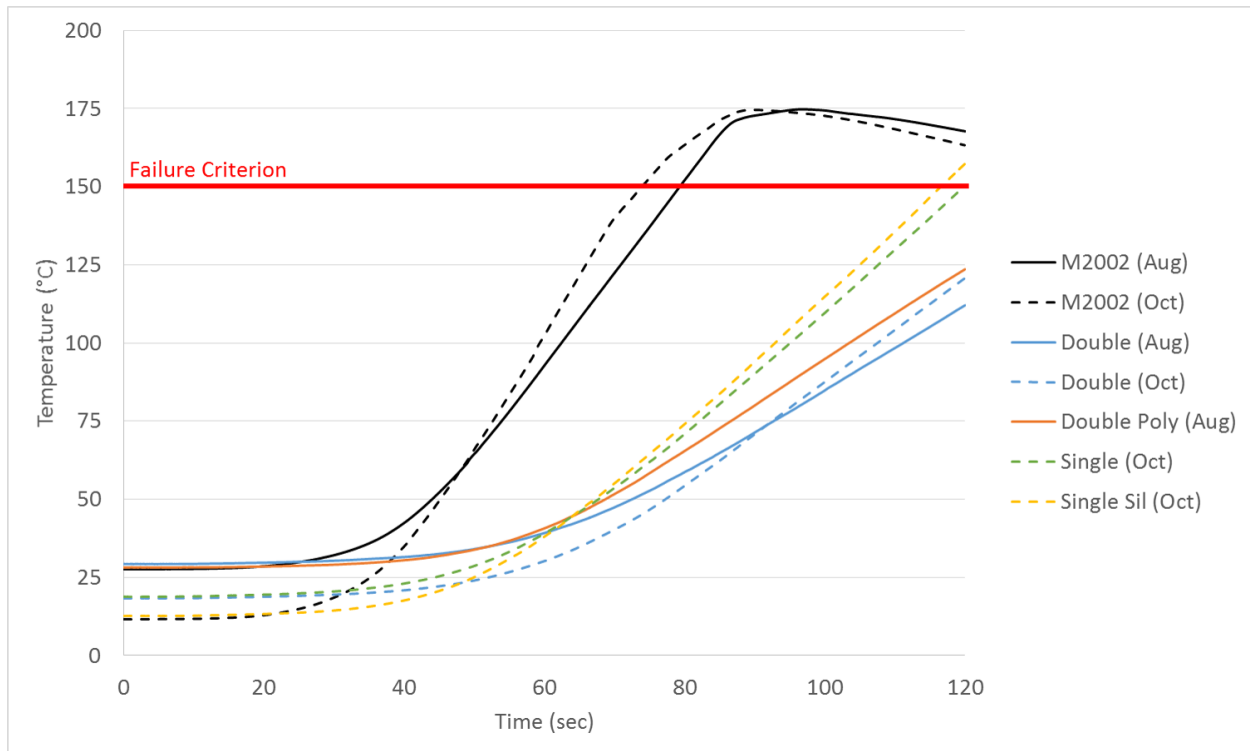


FIGURE 13: AVERAGED 2-INCH "BREATHING ZONE" THERMOCOUPLE DATA SUMMARY

A summary of 10-inch "breathing zone" thermocouple data, as well as the failure criterion temperature, is shown in Figure 14. The data shown is the average of all shelters tested within a given design, as well as the average of both 10-inch thermocouple results for each individual shelter. Performance of 10-inch thermocouple data follows very similar trends to the 2-inch thermocouple data. This is expected as all shelters remained relatively intact structurally and internal flashing or combustion was negligible in all cases. If internal combustion was significant and varied between shelters, 10-inch thermocouple would be expected to reflect these differences between shelter internal heating more dramatically than the 2-inch data. As with the 2-in thermocouple data, no Double design failed the 10-in thermocouple criterion prior to the 120 second test cut off. By using linear extrapolation the Double shelters offered approximately a 140% improvement in the duration of habitability compared to the M2002 for this variable. The Single shelters performed about 89% better.

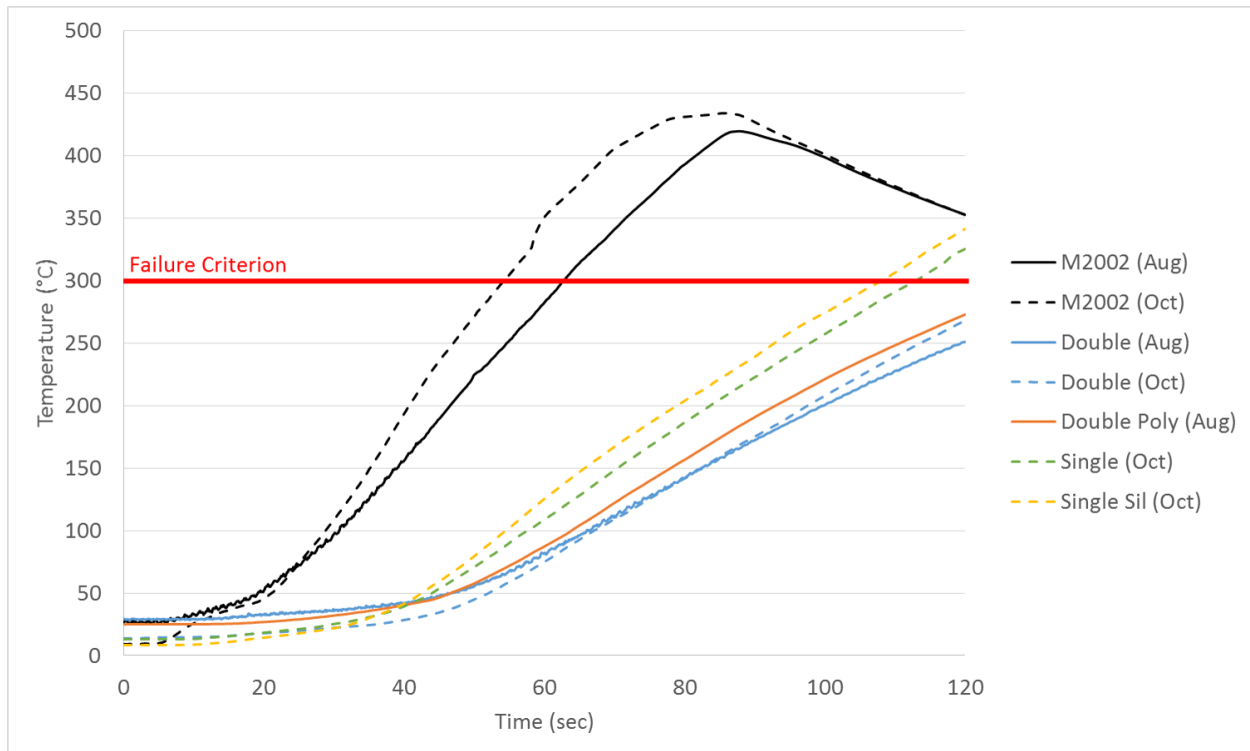


FIGURE 14: AVERAGED 10-INCH THERMOCOUPLE DATA SUMMARY

A summary of internal radiant heat flux data, as well as the failure criterion heat flux, is shown in Figure 15. The data shown is the average of all shelters tested within a given design, as well as the average of all six copper disk slug calorimeter results for each individual shelter. Internal shelter heat flux data followed the same trends as the internal temperature data, except that the Double Shelters tested in October seemed to underperform the Double Polyimide Outer shelters tested in August after about 75 seconds. The cause of this phenomenon is not certain; there is no indication in the video data to suggest flames or gas barrier degradation occurring simultaneously with the upturn in the internal heat flux data. It is possible that the Double Polyimide Outer shelter layup keeps the gas barrier material cooler longer; however, there were no direct measurements of the gas barrier during these tests. Regardless, no CHIEFS shelter failed the internal radiant heat flux criterion prior to the 120 second cut off. Double designs seem likely to fail so far past the conclusion of the testing, that extrapolation would likely be too inaccurate to warrant estimating duration of habitability improvement compared with the M2002. However, linear extrapolation for the Single shelters indicates approximately a 100% improvement in the duration of habitability compared to the M2002 for this variable.

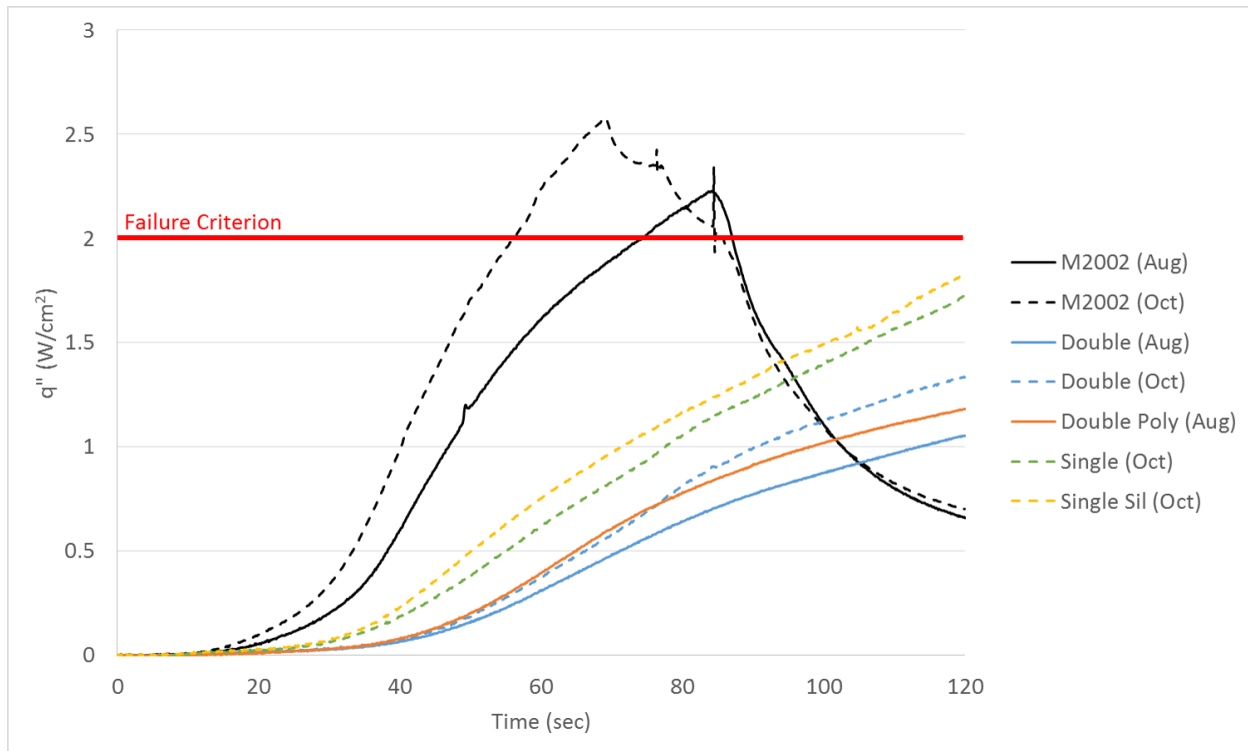


FIGURE 15: AVERAGED INTERNAL RADIANT HEAT FLUX DATA SUMMARY

A summary of carbon monoxide concentration data, as well as the failure criterion concentration, is shown in Figure 16. There is about a 20 second lag between the carbon monoxide concentration data and the thermal response data due to the distance between the gas analyzer and the test rig. The data shown is the average of all shelters tested within a given design. Carbon Monoxide was a concern because the standard M2002 adhesive, and especially the polyimide adhesive, produce significant amounts of carbon monoxide during thermal decomposition. Consequently, the aluminized Kapton was added to the inverted gas barrier configuration primarily to mitigate the direct injection of carbon monoxide and other toxic and or combustible gasses into the shelter. The test failure criterion are designed to approximate the time at which a shelter no longer provides a habitable environment; the first criterion to fail ultimately fails the shelter. Every CHIEFS shelter that failed at least one of the test criterion prior to the 120 second maximum test duration limit failed first due to carbon monoxide. The only shelter not to fail any of the six criterion prior to the 120 second cut off was the Double tested in August; thus, carbon monoxide was the limiting variable in all shelters except the Double in that test. Using linear extrapolation for the Double (August) shelters indicates approximately an 82% improvement in the duration of habitability compared to the M2002 for this variable.

Another notable observation is the significant decrease in the advantage of the CHIEFS shelters compared to the M2002 relative to the other failure criterion. For example, time to failure on the 2-inch thermocouple data was 57% greater than the M2002 for the worst of the CHIEFS performers (Single and Single Silicone); however, for carbon monoxide the same CHIEFS shelters were only 50% better than the M2002 tested in October and 9% worse than the M2002 tested in August. This decrease in the advantage of the CHIEFS shelters is possibly due to the fact that both CHIEFS shelters and M2002 shelters contain roughly the same amount of adhesive. Any failures in the laminates containing adhesive would produce carbon monoxide in all designs. Although the CHIEFS shelters employ the aluminized Kapton in order to contain

gasses generated such as carbon monoxide, there is likely more carbon monoxide produced by the polyimide adhesive in the CHIEFS shelters, and the aluminized Kapton is almost always somewhat compromised by the end of the test. The compromised aluminized Kapton would be less effective at containing carbon monoxide. Also, there is reason to believe that, like the polyimide adhesive, the aluminized Kapton (also a polyimide) may produce carbon monoxide upon thermal decomposition at which point the component intended to contain the gas would begin to contribute to the problem. Finally, internal video data from past testing shows that the M2002 has a tendency to quickly ventilate smoke upon failure of the aluminum on the two laminates which constitute the M2002 layup. Once the aluminum has been compromised, only ceramic fabrics remain in the shelter walls, which allows the shelter to exchange internal gasses readily with the external environment. Given the external environment contains combustion hydrocarbon byproducts, it is likely that all shelters are gaining carbon dioxide and carbon monoxide and losing oxygen; however, this effect is probably more pronounced in the M2002 which may help to equalize the CHIEFS and M2002 carbon monoxide concentrations.

Also of note, the variation in rates of carbon monoxide ingress are significantly more variable and sporadic than the other criterion variables. This is possibly explained by the localized variability in how the aluminized Kapton fails in each individual shelter. The general overall extent of damage, upon post-test inspection, is usually consistent with the overall thermal performance of the shelters; however, video feed shows that the particular rates and behaviors of these failures during testing varies significantly between tests. As a result, there is large variability in the rates and timing of rate changes in the carbon monoxide concentration plot; it is likely that a larger sample pool would result in smoother and more consistent results for this variable.

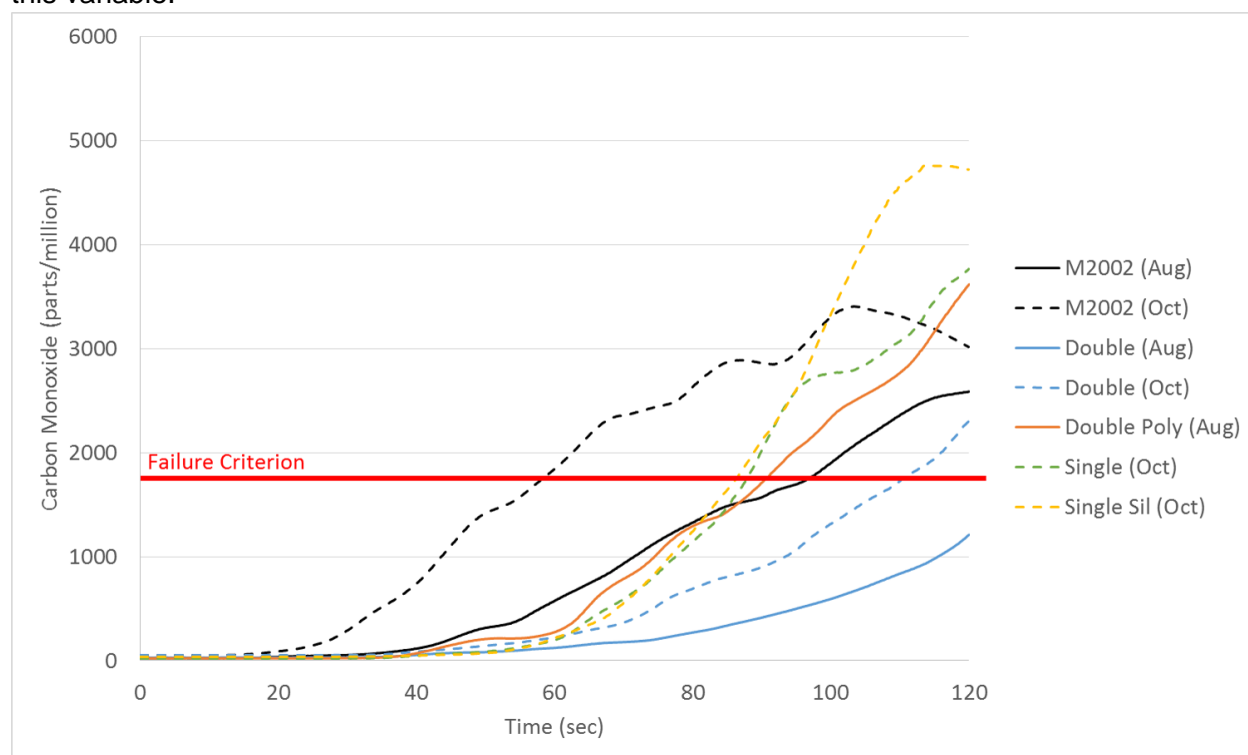


FIGURE 16: AVERAGED INTERNAL CARBON MONOXIDE CONCENTRATION DATA SUMMARY.

A summary of oxygen concentration data, as well as the failure criterion concentration, is shown in Figure 16. There was about a 20 second lag between the oxygen concentration data and the thermal response data due to the distance between the gas analyzer and the test rig.

The data shown is the average of all shelters tested within a given design. CHIEFS shelters exemplified a nearly unchanged oxygen concentration throughout testing until nearly the end of heating. Throughout the 120 second maximum test duration, all CHIEFS shelters remained well above the lower limit as defined by the oxygen failure criterion. The M2002 shelters experienced a more substantial drop in oxygen concentration; however, none of these shelters failed the oxygen criterion either. Unlike carbon monoxide, oxygen concentration was more likely depleted by venting to the external shelter environment upon failure of gas barrier materials, and less likely to be the consequence of shelter decomposition byproducts or chemical reactions. There is some suspicion that carbon monoxide may have reached sufficient temperatures to react with oxygen in the shelter to produce carbon dioxide; however, the extent of this reaction is unknown. Internal video data from past testing shows that the M2002 has a tendency to quickly vent any smoke upon failure of the aluminum on the two laminates which constitute the M2002 layup. Given the external environment contains combustion hydrocarbon byproducts, it is likely that all shelters are gaining carbon dioxide and carbon monoxide and losing oxygen; however, this effect is probably more pronounced in the M2002 which may explain the more significant dip in oxygen levels in the M2002 relative to all CHIEFS shelters.

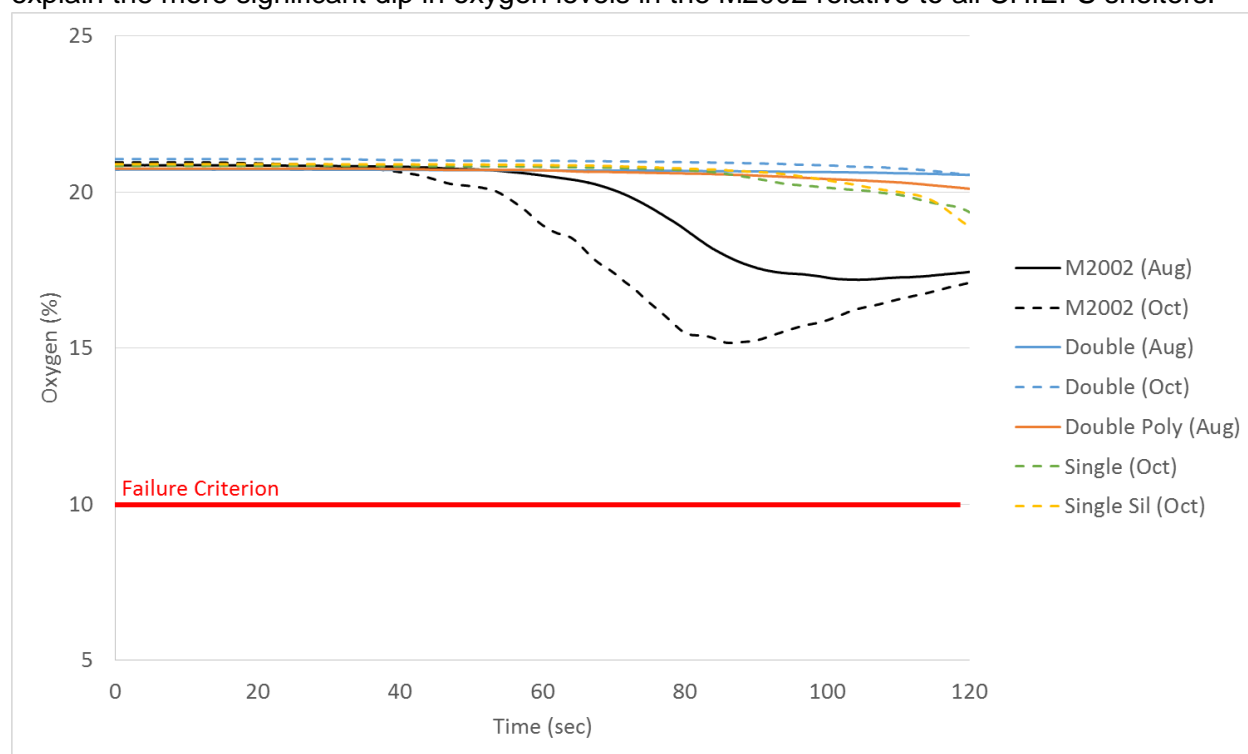


FIGURE 17: AVERAGED INTERNAL OXYGEN CONCENTRATION DATA SUMMARY

The final of the six failure criteria set by the test directors was the observation of heavy smoke or particles within the shelters during testing (as evident in internal shelter video data) or upon post-test inspection of the shelter. This criterion was by far the most arbitrary, but it sought to identify serious threats to the health of the firefighter that would not be reflected by other test instrumentation. The only shelter tested, including M2002s, which elicited a question about the presence of smoke or particles inside the shelter was the Single Silicone. The silicone adhesive used for this laminate has been tested in previous shelter configurations and was known to produce a smoky white powder which formed a residue on the instrumentation inside of the shelter upon thermal decomposition. A picture of the internal shelter instrumentation covered in this residue after the conclusion of one of the two Single Silicone



FIGURE 18: WHITE POWDER COVERING SHELTER INTERIOR INSTRUMENTATION AFTER THE CONCLUSION OF A SINGLE SILICONE SHELTER TEST.

concluded and heating stopped (119 seconds), and at the end of available video data which should be shortly before the test enclosure was removed and the shelter post-test inspection (152 seconds).

Post-test shelter inspection was also a common method of assessing the relative endurance of one shelter design compared with another. The existing test apparatus was not designed to capture the dynamic forces in a real forest fire which would result from heavy and gusty wind conditions. As shelter material decomposes thermally it often becomes more tenuous and brittle, leaving it more vulnerable to thermal performance compromising damage which may result from wind effects.



FIGURE 19: TYPICAL M2002 INTERIOR POST-TEST CONDITION.

shelter tests is shown in Figure 18. It should be noted that in this test, unlike some previous tests, this white powder was produced almost entirely after the shelter had already failed the carbon monoxide test criterion, and largely during the time between the conclusion of heating and when the metal enclosure was removed from the test bed. For this reason, it can be argued that the shelter had already failed when the smoke subjectively became a potential threat, and therefore this test should not be considered evidence for an argument against the use of the silicone glue on grounds of smoke and white powder.

Figure 20 reveals the sequence of smoke ingress at three points: at the time when the shelter failed the test due to exceeding carbon monoxide criterion (87 seconds), at the time when the test was

concluded and heating stopped (119 seconds), and at the end of available video data which

should be shortly before the test enclosure was removed and the shelter post-test inspection

(152 seconds).

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Figure 20 reveals the sequence of smoke ingress at three points: at the time when the shelter failed the test due to exceeding carbon monoxide criterion (87 seconds), at the time when the test was



FIGURE 20: INTERIOR VIDEO DATA SHOWING SUBJECTIVE SMOKE CONCENTRATION INSIDE A SINGLE SILICONE SHELTER AT THREE TIMES: TEST CRITERION FAILURE (87 SECONDS, TOP), TEST CONCLUSION (119 SECONDS, MIDDLE), AND CONCLUSION OF VIDEO DATA (152 SECONDS, BOTTOM).



FIGURE 21: TYPICAL SINGLE INTERIOR POST-TEST CONDITION.

post-test Single shelter is shown in Figure 21; a closer view of the degraded UAI is shown in Figure 22. CHIEFS Single shelters generally remain in better material condition post-test than the M2002; however, there are still often significant degradations. Damage is typically worse near the top center of the shelter. The outer silica fabric is sometimes brittle and can be torn in limited



FIGURE 23: TYPICAL DOUBLE SHELTER INTERIOR POST-TEST CONDITION.

Lacking good controls for this evaluation, no quantitative data was collected on post-test shelter condition; however, photographs of every test specimen and notes were taken which highlight the general observations.

In general, M2002 material conditions are fairly consistent post-test. The outer aluminum foil is always either completely missing, or left as a brittle powdery char. The outer silica fabric is often brittle and can be torn in certain areas. The inner liner (gas barrier) is either completely delaminated, with the aluminum having fallen into the shelter in large sections, or with the aluminum melted into what looks like a porous coating on the fiberglass fabric. The fiberglass fabric is often very brittle with areas missing or easily crumbled away. A photograph of a typical M2002 from the close-out shelter tests is shown in Figure 19.

A

photograph of a typical



FIGURE 22: CLOSE UP OF UAI POST-TEST CONDITION IN SINGLE SHELTER.

locations.

The UAI insulation is typically heavily embrittled and often easily crumbles to dust.

Large well developed expanded graphite particles are heavily concentrated in the UAI fiberglass remnants. The inverted gas barrier fiberglass fabric is brittle in areas, and aluminum foil covers the fabric in beads of aluminum melt. Aluminized Kapton is either completely intact, or burned away with charred edges remaining. The charring typically focuses around seams, but can be widespread over the area at the top of the shelter interior. Video data indicates that the Kapton will openly burn and easily carry a flame. It is not clear the process in which this combustion takes place because it is generally known that polyimide does not burn openly. When comparing the post-test conditions of CHIEFS shelters to the M2002, it should be noted that the M2002 was tested for a shorter period of time and

consequently material conditions would be even worse than the observed for the M2002 if it was exposed to heating for the full duration of the CHIEFS shelters it is compared to.

CHIEFS Double shelters generally remain in the best post-test material condition of all shelters. Damage is typically worse near the top center of the shelter and focuses near the seams. The outer silica fabric is sometimes brittle and can be torn in limited locations. The outer UAI insulation is typically heavily embrittled and often easily crumbles to dust. The inner UAI insulation often remains pliable with limited regions of brittle or crumbling fibers. The inverted gas barrier fiberglass fabric can be brittle, but not always, and aluminum foil is either intact or covers the fabric in beads of aluminum melt. Aluminized Kapton is largely intact, but some limited charred edges or burned out sections focus mostly around seams at the top of the shelter. A photograph of a typical Double from the close-out shelter tests is shown in Figure 23.

Small-Scale Convective Test Results

At the conclusion of full scale close-out shelter testing, a series of small scale convective tests were run on the shelter wall materials used in the full scale tests. The small scale convective test is an effective method of measuring the thermal performance of shelter materials without the confounding effects of a full shelter. Furthermore, the full scale shelter test environment can be somewhat variable, whereas the small scale convective test rig provides relatively even and consistent heating with a well-controlled and calibrated heat source. By testing CHIEFS full scale shelter materials in the small-scale convective test setup, relative insulation thermal performance could be assessed between options, which can help to understand the amplitude of interfering effects which may have influenced the full scale shelter test results. An explanation of the small-scale convective test rig and test methods is found in the Small-Scale Convective Test Setup section above.

Material layups tested were the same as the full scale shelter tests in August and October 2017, except that the M2002 Polyimide Outer was not tested in the small-scale convective test. A description of the material configurations tested can be found in Table 4. In

TABLE 4: SMALL-SCALE CONVECTIVE TEST MATRIX.

Layup Number	Layup Name	Areal Mass		Compressed Thickness	
		g/m ²	Oz/yd ²	cm	inch
	M2002	498	14.7	0.076	0.030
1	Double	658	19.4	0.831	0.327
2	Single	573	16.9	0.333	0.131
3	Single Silicone	570	16.8	0.259	0.102

the small-scale tests, three identical samples were prepared for a given material configuration prior to the test. During the test, the pre-test calibration was run to ensure the target 8 +/- .4 W/cm² heat flux from the burner, and then the three identical samples were exposed sequentially until the coolest gas barrier thermocouple recorded a temperature of 200 °C at which point the sample was removed. After the three identical samples were exposed, a post-test calibration was conducted to ensure the exposure heat flux was still within the target. The results of these tests are shown in Figure 24. Note that each line on this chart is an average of the three samples tested in each of two test runs. By not averaging the two runs (total of six

samples for each material configuration), some idea of the variation between exposures can be observed. The results of the test did not match the amplitude of differences between each candidate exactly; however, the relative performance was in good agreement with full scale shelter test data.

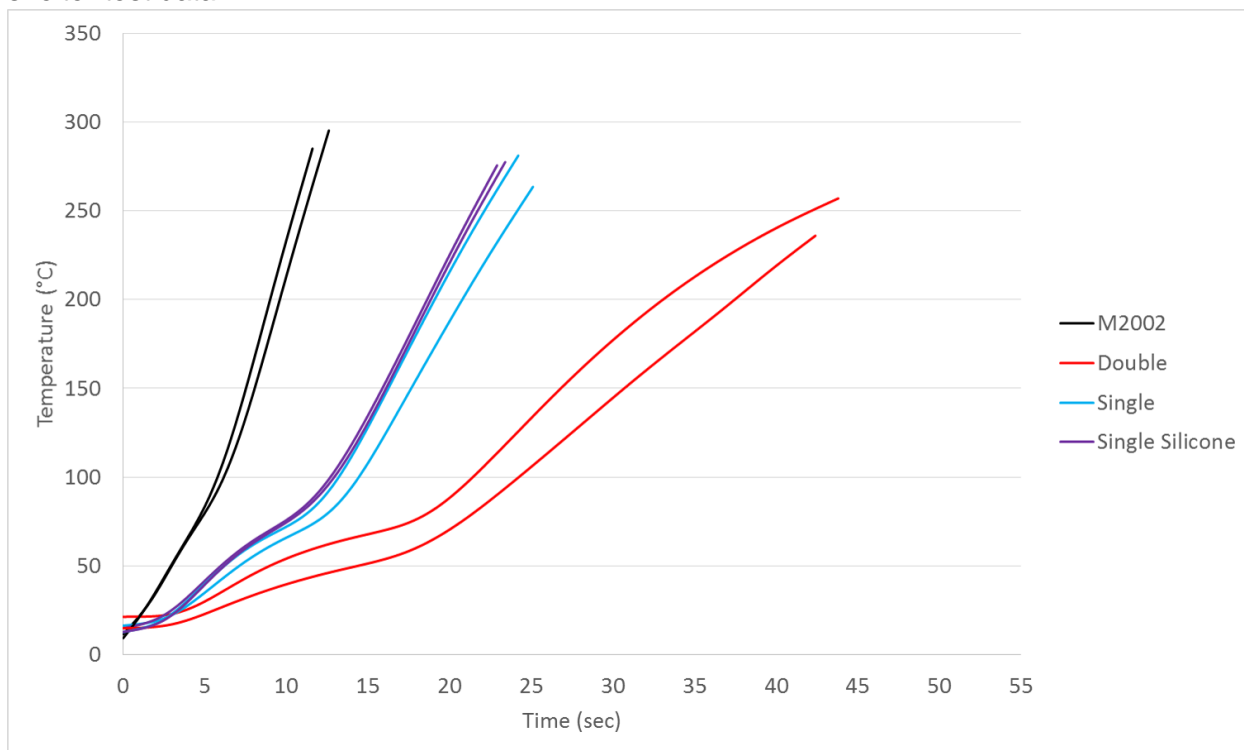


FIGURE 24: SMALL SCALE CONVECTIVE TEST RIG RESULTS OF LAYUPS USED ON FULL SCALE CLOSE-OUT SHELTERS TESTED.

Concluding Remarks

Of all NASA shelters tested during the nearly four year CHIEFS task, the close-out fire shelters demonstrated the best performance for their weight. The Double shelter (August 2017) was the only shelter to exceed the maximum 120 second test duration without failing any of the six test criterion. The Double (October 2017) and Double Polyimide Outer also survived all other test criterion prior to the 120 second cutoff, except carbon monoxide. The only other CHIEFS design which was able to survive the 120 seconds without failing the 2-inch thermocouple test criterion was the M2002-Heavy (Gen 1) shelter tested in 2015; however, the M2002-Heavy was an 8 lb shelter (approximately 63% heavier than the Double). Small-scale convective tests were conducted to confirm the observed relative shelter performance, and relative results of this better controlled test were consistent with the full scale results.

The tests were conducted in two periods, August 2017 and October 2017. Four fire shelter concepts were tested and compared by the duration in which each shelter concept was able to provide a habitable interior environment relative to other candidates and most importantly the current fire shelter, the M2002. Habitability was defined by the period of time that the shelter was undergoing heating without having exceeded a “failure” threshold in any one of the six different test criterion. The six test criterion were 2-inch thermocouple temperature, 10-inch thermocouple temperature, internal radiant heat flux, carbon monoxide

concentration, oxygen concentration, and a subjective analysis of heavy smoke or airborne particles present in the shelter interior.

Close-out shelter performance owes some of its success to a novel binary gas barrier concept. This concept makes use of an inverted fiberglass-aluminum foil laminate fabricated using high temperature polyimide adhesive, and backed by an aluminized Kapton film. The adhesive produces significant amounts of carbon monoxide when it undergoes thermal degradation; consequently, the aluminized Kapton film was added to mitigate the ingress of this carbon monoxide (and other undesirable gaseous biproducts) to the shelter interior. Nonetheless, the first of the six criterion failed by CHIEFS close-out shelters was almost unanimously carbon monoxide.

At the conclusion of the 2017 fiscal year, funding for the CHIEFS task expired and sources of continued funding into the 2018 fiscal year were not able to be secured. Consequently, the close-out fire shelter tests described in this paper represent the final round of fire shelter candidates generated under CHIEFS. At the time of this writing, a recent National Wildfire Coordinating Group Fire Shelter Sub-Committee meeting concluded that the CHIEFS Double and Single shelters would be two of the three down-selected candidates carried forward to mechanical wear testing during the upcoming 2018 fire season. During this wear testing, a number of shelters for each the Single and Double configurations would be carried by firefighters in the field for the duration of the fire season. After the fire season, these test shelters will be inspected for damage due to the wear and tear associated with firefighting. After reviewing these results, a final decision will be made on any potential replacements for the current M2002. The Double shelter is currently being considered for a vehicle carried design; the Single shelter is being considered as a direct replacement for the M2002 as a shelter carried on the person of the firefighters in the field. Fire shelters are required by the Forest Service to be carried by personnel fighting wildfire. The fire shelter program is managed by the Forest Service at the Missoula Technology Development Center (MTDC) in Missoula, Montana.

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